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# IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

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| In re Application | | PATENT APPLICATION |
| Inventor(s): | Mark A. Lemkin<br>William A. Clark<br>Thor N. Juneau<br>Allen W. Roessig | |
| SC/Serial No.: | Unknown | |
| Filed: | Herewith | |
| Title: | STRUCTURE FOR ATTENUATION OR CANCELLATION OF QUADRATURE ERROR | |

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_______________________(Signature)
Johann S. Mercado
Signature Date: June 13, 2000

## UTILITY PATENT APPLICATION TRANSMITTAL LETTER UNDER 37 C.F.R §1.53(b)

Box PATENT APPLICATION
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Washington, DC 20231

Sir:

Transmitted herewith for filing is the patent application identified as follows:

Inventor(s): Mark A. Lemkin, William A. Clark, Thor N. Juneau, Allen W. Roessig

Title: STRUCTURE FOR ATTENUATION OR CANCELLATION OF QUADRATURE ERROR

No. of pages in Specification: 42; No. of Claims: 20.

No. of Sheets of Drawings: 7; Formal: __, Informal: X.





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Jc857 U.S. PTO 09/593593 06/13/00
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Also enclosed are:

_X_ A Declaration.

_X_ An Assignment and Recordation Form Cover Sheet.

_X_ A Power of Attorney.

_X_ A Statement Claiming Small Entity Status.

_X_ An Information Disclosure Statement under 37 C.F.R. §1.56.

The filing fee pursuant to 37 C.F.R. §1.16 is determined as follows:

| | No. Filed | | No. Extra | | Rate Small Entity/ Other Than Small Entity | | |
|---|---|---|---|---|---|---|---|
| Basic Fee | | | | | $345.00<br>$690.00 | = | $345.00 |
| Total Claims | 20 - 20 | = | 0 * | X | $ 9.00<br>$ 18.00 | = | $-0- |
| Independent Claims | 4 - 3 | = | 1 * | X | $ 39.00<br>$ 78.00 | = | $ 39.00 |
| First Presentation of Multiple Dependent Claim(s) | ___ | | | | $130.00<br>$260.00 | = | $ |
| | | | | | Total | = | $384.00 |

*If the difference is less than zero, enter "0".

_ Please charge Deposit Account No. 06-1325 in the amount of $___. A duplicate copy of this authorization is enclosed.

_X_ A check in the amount of $424.00 to cover the filing fee ($384.00), and assignment recording fee ($40.00), if applicable, is enclosed.

_X_ The Commissioner is hereby authorized to charge underpayment of any additional fees (including those listed below) or credit any overpayment associated with this communication to Deposit Account No. 06-1325. A duplicate copy of this authorization is enclosed.

  _X_ Any additional filing fees under 37 C.F.R. §1.16.

  _X_ Any patent application processing fees under 37 C.F.R. §1.17.

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This application is filed pursuant to 37 C.F.R. §1.53(b) in the name of the above-identified Inventors.

_X_ This application claims priority to an earlier-filed Provisional patent application, as set forth more fully in this application.

Please direct all correspondence concerning the above-identified application to the following address:


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Respectfully submitted,

Date: June 13, 2000

By: Larry E. Vierra<br>
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|---|---|---|
| In re Application | ) | PATENT APPLICATION |
| Inventor(s): Lemkin, et al. | ) | |
| SC/Serial No.: Unknown | ) | |
| Filed: Herewith | ) | |
| Title: STRUCTURE FOR ATTENUATION OR CANCELLATION OF QUADRATURE ERROR | ) | |

**STATEMENT CLAIMING SMALL ENTITY STATUS**
**37 C.F.R §1.9(f) AND §1.27(c) - SMALL BUSINESS CONCERN**

I hereby declare that I am:

___ The owner of the small business concern identified below.

X An official of the small business concern empowered to act on behalf of the concern identified below.

Name: Integrated Micro Instruments, Inc.

Address: 2140 Shattuck Avenue, Suite 205, Berkeley, California 94704

I hereby declare that the above identified small business concern qualifies as a small business concern as defined in 13 C.F.R. §121.12, and reproduced in 37 C.F.R. §1.9(d), for purposes of paying reduced fees under Section 41(a) and (b) of Title 35 U.S.C. in that the number of employees of the concern, including those of its affiliates, does not exceed 500 persons. For purposes of this statement, (1) the number of employees of the business concern is the average over the previous fiscal year of the concern of the persons employed on a full-time, part-time or temporary basis during each of the pay periods of the fiscal year, and (2) concerns are affiliates of each other when either, directly or indirectly, one concern controls or has the power to control the other, or a third-party or parties controls or has the power to control both.

I hereby declare that rights under contract or law have been conveyed to and remain with the small business concern identified below with regard to the invention identified by the above TITLE and INVENTORS, and described in:

X the Specification filed herewith
___ the Application having the above SC/Serial No. and Filed date
___ Patent No.__________ issued __________

If the rights held by the above-identified small business concern are not exclusive, each individual, concern or organization having rights to the invention is listed below* and no rights to the invention are held by any person, other than the inventor, who could not qualify as an independent inventor under 37 C.F.R. §1.9(c) or by any concern which would not qualify as a small business concern under 37 C.F.R. §1.9(d) or a nonprofit organization under 37 C.F.R. §1.9(e).

NAME: ______________________________

ADDRESS: ______________________________

[ ] Individual  [ ] Small Business Concern  [ ] Nonprofit Organization

NAME: ______________________________

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[ ] Individual  [ ] Small Business Concern  [ ] Nonprofit Organization

I acknowledge the duty to file, in this application or patent, notification of any change in status resulting in loss of entitlement to small entity status prior to paying, or at the time of paying, the earliest of the issue fee or any maintenance fee due after the date on which status as a small business entity is no longer appropriate. (37 C.F.R. §1.28(b)).

Name of Person Signing: Mark Alan Lemkin

Title of Person Signing: Vice President

Address of Person Signing: 2140 Shattuck Avenue, # 205, Berkeley, CA 94704

Signature: Mark A Lemkin

Date: 5/22/00

*******************************************************************

* Note: Separate statements are required from each named person, concern or organization having rights to the invention averring to their status as small entities. (37 C.F.R. §1.27).

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## Title 37, Code of Federal Regulations, §1.9(c-f)

(c) An **independent inventor** as used in this chapter means any inventor who (1) has not assigned, granted, conveyed, or licensed, and (2) is under no obligation under contract or law to assign, grant, convey, or license, any rights in the invention to any person who could not likewise be classified as an independent inventor if that person had made the invention, or to any concern which would not qualify as a small business concern or a nonprofit organization under this section.

(d) A **small business concern** as used in this chapter means any business concern meeting the size standards set forth in 13 C.F.R. Part 121 to be eligible for reduced patent fees. Questions related to size standards for a small business concern may be directed to: Small Business Administration, Size Standards Staff, 409 Third Street, SW, Washington, DC 2041.

(e) A **nonprofit organization** as used in this chapter means (1) a university or other institution of higher education located in any country; (2) an organization of the type described in section 501(c)(3) of the Internal Revenue Code of 1954 (26 U.S.C. 501(c)(3)) and exempt from taxation under section 501(a) of the Internal Revenue Code (26 U.S.C. 501(a)); (3) any nonprofit scientific or educational organization qualified under a nonprofit organization statute of a state of this country (35 U.S.C. 201(i)); or (4) any nonprofit organization located in a foreign country which would qualify as a nonprofit organization under paragraphs (e) (2) or (3) of this section if it were located in this country.

(f) A **small entity** as used in this chapter means an **independent inventor**, a **small business concern** or a **nonprofit organization** eligible for reduced patent fees.

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## Title 13, Code of Federal Regulations, §121.12

**121.12 Small business for paying reduced patent fees.** (a) Pursuant to Pub. L. 97-247, a small business concern for purposes of paying reduced fees under 35 U.S. Code 41 (a) and (b) to the Patent and Trademark Office means any business concern (1) whose number of employees, including those of its affiliates, does not exceed 500 persons and (2) which has not assigned, granted, conveyed, or licensed, and is under no obligation under contract or law to assign, grant, convey or license, any rights in the invention to any person who could not be classified as an independent inventor if that person had made the invention, or to any concern which would not qualify as a small business concern or a nonprofit organization under this section. For the purpose of this section concerns are affiliates of each other when either, directly or indirectly, one concern controls or has the power to control the other, or a third party or parties controls or has the power to control both. The number of employees of the business concern is the average over the fiscal year of the persons employed during each of the pay periods of the fiscal year. Employees are those persons employed on a full-time, part-time or temporary basis during the previous fiscal year of the concern.

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# STRUCTURE FOR ATTENUATION OR CANCELLATION OF QUADRATURE ERROR

## INVENTORS


Mark A. Lemkin
William A. Clark
Thor N. Juneau
Allen W. Roessig


**CERTIFICATE OF MAILING BY "EXPRESS MAIL" UNDER 37 C.F.R. § 1.10**

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Johann S. Mercado
Signature Date: June 13, 2000

# STRUCTURE FOR ATTENUATION OR CANCELLATION OF QUADRATURE ERROR

INVENTORS:

Mark A. Lemkin, William A. Clark, Thor N. Juneau, Allen W. Roessig

## CROSS-REFERENCE TO RELATED APPLICATION

This application claims priority to Provisional Application Serial No. 60/139,352 filed June 15, 1999 entitled "VIBRATORY RATE GYROSCOPE WITH QUADRATURE-ERROR CORRECTION CAPABILITY."

## IDENTIFICATION OF GOVERNMENT INTEREST

This invention was made with Government support under F49620-98-C-0082 awarded by the Air Force Office of Scientific Research. The Government has certain rights in the invention.

## BACKGROUND OF THE INVENTION

### Field of the Invention

This invention relates generally to moving structures and more particularly, to vibratory rate gyroscopes. This invention may be used to reduce error caused by imperfections in implementation of such structures.

Description of the Related Art

Rate gyroscopes are sensors that measure rotation rate. Rate gyroscopes have uses in many commercial and military applications including, but not limited to, inertial navigation, vehicular skid control, and platform stabilization.

A vibratory rate gyroscope is a sensor that responds to a rotation rate by generating and measuring Coriolis acceleration. Coriolis acceleration is generated by an object, such as a proof-mass, that has some velocity relative to a rotating reference frame. In vibratory rate gyroscopes, one or more proof-masses are often suspended from flexures and made to oscillate thus providing a velocity necessary to generate Coriolis acceleration. Measurement of the resulting Coriolis acceleration can then yield an estimate of the rotation rate of the sensor.

An idealized version of a single-mass sensor is shown in Figure 1. In this figure a three-dimensional, mutually orthogonal coordinate system is shown for reference. The axes are arbitrarily labeled “X”, “Y”, and “Z” to enable description of background material as well as the invention. Oscillation that is largely coincident with the X-axis is often referred to as the drive-mode or driven-mode. Coriolis acceleration is generated perpendicular to the drive-mode along the sense-mode, which lies largely along the Y-axis. The Coriolis acceleration generated by the system shown in Figure 1 is given by:

$$a_{Coriolis}=2\Omega_z D_x \omega_x \cos(\omega_x t) \qquad \text{Equation 1}$$

where $a_{Coriolis}$ is the Coriolis acceleration generated along the sense-mode, $\Omega_z$ is the rotation rate to be measured about the Z-axis, and $\omega_x$ and $D_x$ are the frequency and magnitude of drive-mode oscillation, respectively. The Coriolis acceleration causes an oscillatory displacement of the sensor along the sense-mode with magnitude proportional to the generated Coriolis acceleration. Ideally, the drive-mode is coincident with the forcing means used to sustain oscillation (located along the X-axis or drive-axis), and the sense-mode is coincident with the sensing means used to detect displacements due to Coriolis acceleration (located along the Y-axis or sense-axis).

The simplified schematic of Figure 1 shows proof-mass 52, attached to substrate 51 via a compliant suspension that may be modeled by two springs 50a, and 50b. Typically the compliant suspension is designed such that the suspension may be modeled by an orthogonal decomposition into two springs: spring 50b lying along the sense-mode and spring 50a lying along the drive-mode. Mathematically this translates into a goal of being able to decompose the suspension into a diagonal spring matrix when an orthogonal coordinate system comprising the sense-axis and the drive-axis is chosen. The design and fabrication of the proof-mass and the suspension will dictate the actual orientation of the drive- and sense-modes with respect to the driving and sensing axes. Often, the suspension may have small, off-diagonal spring-



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matrix components due to, for example, processing imperfections during a reactive-ion-etching step, or misalignment of the drive and sense-axes to their corresponding modes.

Figure 2 shows a simplified schematic of a dual-mass gyroscope. In a dual-mass gyroscope, a differential oscillation of proof-masses 62a and 62b along the drive-mode lead to a differential Coriolis-acceleration induced oscillation along the sense-mode. The suspension of a dual mass gyroscope may be modeled by springs 60a, 60b, and 60c. Often the suspension may be further decomposed to have additional springs (not shown) that provide restoration of common-mode deflections along the X-axis. The operation of dual-mass gyroscopes is well known by those skilled in the art, with example dual-mass gyroscopes described in Clark et al. US Patent Application 09/321,972 filed May 28, 1999; Geen, US Patent 5,635,640, Issued June 3, 1997; Geen, US Patent 5,635,638, Issued June 3, 1997; Ward et al., US Patent 5,747,961, Issued May 5, 1998; Lee et al., US Patent 5,757,103, Issued May 26, 1998.

It is important to understand that the Coriolis acceleration signal along the sense-axis is in phase with velocity of the drive-mode, which is 90 degrees out-of-phase with proof-mass displacement along the drive-mode. While the Coriolis acceleration is 90 degrees out-of-phase with the proof-mass displacement along the drive-mode, displacements along the sense-mode due to Coriolis acceleration may have a different phase relationship to the proof-mass displacement along the drive-mode depending on several factors



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including: the relative values of drive-mode oscillation frequency to sense-mode resonant frequency, and the quality factor of the sense-mode.

Forces are often applied to vibratory-rate gyroscopes to generate or sustain proof-mass oscillation. Forces may be applied to the gyroscope using variable air-gap capacitors formed between one or more plates or conductive nodes attached to the proof-mass and one or more plates or conductive nodes attached to the substrate. Note that electrostatic forces result between charged capacitor plates. The magnitude and direction of the force is given by the gradient of the potential energy function for the capacitor as shown below.

$$\vec{F} = -\nabla U = -\nabla\left[\frac{Q^2}{2C(x,y,z)}\right] \qquad \text{Equation 2}$$

As an example, an appropriate oscillation in the gyroscope may be generated using a force along a single axis (e.g. the X-axis). Equation 2 implies that any capacitor that varies with displacement along the X-axis will generate an appropriate force. An implementation of a pair of such capacitors is shown in Figure 3. This capacitor configuration has a number of advantages including ample room for large displacements along the X-axis without collisions between comb fingers. By applying differential voltages with a common mode bias $V_{DC}$ across electrically conductive comb fingers 72a, 73a and 72b, 73b a force that is independent of X-axis displacement and linear with control voltage, $v_x$ is created.



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$$
\begin{aligned}
V_1 &= V_{DC} - v_x \\
V_2 &= V_{DC} + v_x \\
F_x &= \frac{1}{2}\frac{\partial C}{\partial x}V_2^2 - \frac{1}{2}\frac{\partial C}{\partial x}V_1^2 = 2\frac{C_0}{X_0}V_{DC}v_x
\end{aligned}
\qquad \text{Equation 3}
$$

where $C_0$ and $X_0$ are the capacitance and X-axis air-gap at zero displacement respectively. An equivalent method of applying forces chooses $V_1$, $V_2$ such that:

$$
\begin{aligned}
V_1 &= V_{DC} - v_x \\
V_2 &= -V_{DC} - v_x
\end{aligned}
\qquad \text{Equation 4}
$$

Note that in both of these cases the magnitude of the force is proportional to the control voltage, $v_x$, and the DC bias voltage, $V_{DC}$. This permits the magnitude and direction of the force to be directly controlled by varying either $v_x$ or $V_{DC}$ while maintaining the other voltage constant. Other prior-art work has used parallel-plate capacitors, or piezoelectric transduction elements to effect motion.

Many methods are known that sense motion or displacement using air-gap capacitors. Details of capacitive measurement techniques are well known by those skilled in the art. These methods may be used for detection of displacement due to Coriolis acceleration, measuring quadrature error (described below), or as part of an oscillation-sustaining loop. Often a changing voltage is applied to two nominally equal-sized capacitors, formed

by a plurality of conductive fingers, with values that change in opposite directions in response to a displacement. For example, one method applies voltages to these sensing capacitors in a manner that generates a charge that is measured by a sense interface (see for example: Boser, B.E., Howe, R.T., "Surface micromachined accelerometers," IEEE Journal of Solid-State Circuits, vol.31, pp. 366-75, March 1996., or Lemkin, M., Boser B.E., "A micromachined fully differential lateral accelerometer," CICC Dig. Tech. Papers, May 1996, pp. 315-318.). Another method uses a constant DC bias voltage applied across two sensing capacitors. Any change in the capacitance values results in current flow that is detected by a sense interface (See for example: Clark, W.A., Micromachined Vibratory Rate Gyroscopes, Doctoral Dissertation, University of California, 1997; Roessig, T.A., Integrated MEMS Tuning Fork Oscillators for Sensor Applications, University of California, 1998; Nguyen, C. T.-C., Howe, R.T., "An integrated CMOS micromechanical resonator high-Q oscillator," IEEE JSSC, pp. 440-455, April 1999). Furthermore, some methods of capacitive detection use time-multiplexing (See for example: M. Lemkin, B.E. Boser, "A three-axis micromachined accelerometer with a CMOS position-sense interface and digital offset-trim electronics," IEEE Journal of Solid-State Circuits, pp. 456-68, April 1999) or frequency multiplexing (See for example Sherman, S.J, et. al., "A low cost monolithic accelerometer; product/technology update," International Electron Devices Meeting, San Francisco, CA, Dec. 1992, pp. 501-4) to enable electrostatic forces to be applied to a microstructure and displacement or



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motion of the microstructure to be sensed using a single set of capacitors. An example of an application in which time- or frequency-multiplexing of capacitor function in such a manner may prove useful includes a force-feedback loop.

Provided with a controllable force applied to a structure and a measure of the structure's deflection, the structure may be driven into oscillation using feedback. Oscillation is achieved by measuring the structure's displacement or velocity then determining the magnitude, and/or phase of the force or forces to apply to the structure. The measurement of the structure's displacement and the force(s) applied may be electrostatic as described above. In a dual-mass gyroscope the position or velocity detected by the sense interface often reflects relative motion between the two masses, and the forces applied to the two masses may contain a differential force component. Many methods that sustain drive-mode oscillation are known by those skilled in the art. Descriptions of oscillation-sustaining circuits and techniques may be found in, for example (Roessig, T.A., Integrated MEMS Tuning Fork Oscillators for Sensor Applications, University of California, 1998; Nguyen, C. T.-C., Howe, R.T., "An integrated CMOS micromechanical resonator high-Q oscillator," IEEE JSSC, pp. 440-455, April 1999; Lemkin, et al. US Patent Application 09/322,840 Filed May 28, 1999; Putty et al., US Patent 5,383,362, Issued January 24, 1995; Ward, US Patent 5,600,064, Issued February 4, 1997). Note that driven-mode oscillations may also be excited open loop, see for example Geiger, W. et al. "A mechanically controlled oscillator," *Transducers 99*, Sendai Japan, June7-10, 1999 pp. 1406 - 09.



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Because of imperfections introduced in the manufacturing process, the gyroscope driven-mode and sense-axis may not be perfectly orthogonal. Imperfections in elements of the suspension are one possible source of this non-orthogonality. A non-orthogonal relationship between the driven-mode and the sense-axis may cause a sense capacitance change proportional to displacement in the drive-mode to appear along the sense axis. When the sense-capacitance change is detected using a position-sense interface, an output signal substantially in-phase with displacement may result.

This undesirable signal is termed quadrature error. Since Coriolis acceleration is in phase with velocity, these two signals are ideally separated by 90 degrees of phase, hence the name quadrature error. Note, however, the magnitude of the quadrature error may be many orders of magnitude greater than the quantity of interest: Coriolis acceleration.

Due to the similarity and relative magnitude of the two signals, quadrature-error can contaminate if not overwhelm the sensor output. For example, a small amount of phase lag in detection circuitry can lead to quadrature error leakage into the sensor output. Results of this leakage may include large sensor output offsets, output-offset drift, and noise. In addition, large quadrature-error signals may cause saturation of sense-mode interfaces. Quadrature-error has been addressed in different ways in prior art gyroscopes including forcing mechanisms (Ward, US Patent 5,600,064, Issued February 4, 1997; Clark et al, US Patent 5,992,233, Issued November 30, 1999; Clark et al., US Patent Application 09/321,972, Filed May 28, 1999)

and carefully-designed, well-controlled fabrication of mechanical structures (Geen, J. "A path to low cost gyroscopy," *IEEE Solid-State Sensor and Actuator Workshop*, Hilton Head Island, SC, June 8 - 11,1998, pp 51-4.). A good description of sources of quadrature-error and the effect on vibratory-rate gyroscopes may be found in Clark, W.A., Micromachined Vibratory Rate Gyroscopes, Doctoral Dissertation, University of California, 1997.

## SUMMARY OF THE INVENTION

It is an object of the present invention to provide a device for causing a vibrating mass to vibrate, absent a Coriolis force, more precisely along a driven axis substantially orthogonal to a sense axis. Since deflections along the sense axis may be sensed to infer a rotation rate in a vibratory-rate gyroscope, improved sensor output may be attained when the mass is caused to vibrate more precisely along a drive axis.

It is a further object of the present invention to provide a device capable of causing a vibrating mass to vibrate, absent a Coriolis force, more precisely along a driven axis using a feedback network in which quadrature-error is measured and actively fed back to cause the vibrating mass to vibrate, absent a Coriolis force, more precisely along a driven axis in the presence of disturbances such as temperature fluctuations, flicker noise, or variations in mechanical stress.



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It is a further object of the present invention to provide a device capable of causing a vibrating mass to vibrate, absent a Coriolis force, more precisely along a driven axis in an area-efficient manner.

It is a further object of the present invention to provide a device capable of causing a vibrating mass to vibrate, absent a Coriolis force, more precisely along a driven axis where the vibrating mass is formed from a single layer of conductive material.

These and other objects are accomplished, according to an embodiment of the present invention, by a movable microstructure comprising a substrate, and a proof-mass disposed above the substrate. The movable microstructure includes a first finger set comprising two or more first fingers affixed to the substrate and extending substantially parallel to a defined displacement axis towards the proof-mass. The movable microstructure further includes a second finger set comprising at least one second finger, each member of the second finger set extending substantially parallel to the displacement axis from the proof-mass, terminating between two first fingers. Each second finger is substantially closer to one of the two first fingers between which it terminates. The first finger set, in conjunction with the second finger set, form two terminals of a capacitor. An electrical circuit is included that provides a voltage across the capacitor to generate a position-dependent force, the position-dependent force having a component along an axis substantially orthogonal to the displacement axis, the magnitude of the

position-dependent force varying in proportion to displacement along the displacement axis.

## BRIEF DESCRIPTION OF THE DRAWINGS

For a better understanding of the nature and objects of the invention, reference should be made to the following detailed description taken in conjunction with the accompanying drawings, in which:

Figure 1 is a schematic diagram of a proof-mass, connected to a substrate by a suspension.

Figure 2 is a simplified schematic diagram of a dual-mass gyroscope.

Figure 3 is a perspective view of a capacitor that is convenient for sensing or forcing motion along a drive-axis.

Figure 4 is a perspective view of a first embodiment of the invention.

Figure 5A is a plan view of a second embodiment of the invention, showing a proof-mass having oscillatory behavior that may appear as quadrature error.

Figure 5B is a plan view of a second embodiment of the invention, showing correction of undesired oscillatory behavior.

Figure 6A is a plan view of a third embodiment of the invention, showing a proof-mass having oscillatory behavior that may appear as quadrature error.

Figure 6B is a plan view of a third embodiment of the invention, showing correction of undesired oscillatory behavior.



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Figure 7A is a plan view of a fourth embodiment of the invention, showing a proof-mass having oscillatory behavior that may appear as quadrature error.

Figure 7B is a plan view of a fourth embodiment of the invention, showing correction of undesired oscillatory behavior.

Figure 8A is a plan view of a fifth embodiment of the invention, showing two proof-masses having oscillatory behavior that may appear as quadrature error.

Figure 8B is a plan view of a fifth embodiment of the invention, showing correction of undesired oscillatory behavior.

Figure 9A is a plan view of a sixth embodiment of the invention, showing two proof-masses having oscillatory behavior that may appear as quadrature error.

Figure 9B is a plan view of a sixth embodiment of the invention, showing correction of undesired oscillatory behavior.

Figure 10 is a plan view of a simplified sense-element with quadrature-correction structures.

Figure 11 is a schematic diagram of a vibratory-rate gyroscope including closed loop quadrature-error correction.

Like reference numerals refer to corresponding parts throughout all the views of the drawings.



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## DETAILED DESCRIPTION

A novel quadrature-nulling structure in accordance with the present invention reduces quadrature-error in single-mass vibratory-rate gyroscopes (VGR's), dual-mass VGR's, and single- or dual-mass frame-based VGR's. It will be well understood by those of average skill that the structure is to be used with an oscillation-sustaining loop and a sense axis position-sensing interface. As described in the section titled Description of the Related Art, these methods and configurations are well known by those skilled in the art. To prevent unnecessary distraction from the subject of the invention, air-gap capacitors comprising the oscillation-sustaining loop and the sense-axis position-sensing interface are not shown in the following detailed description of the invention.

Figure 4 shows a first embodiment of the present invention. In this embodiment, a quadrature-nulling structure includes at least one comb-finger set comprising one first comb-finger 100a located adjacent to one second comb finger 101a. Often a plurality of comb-finger sets will be required to attain sufficient quadrature-correction force to cancel quadrature-error. Note that multiple comb-finger sets are formed adjacent to each other as illustrated in Figure 4 (i.e. second comb-finger set 100b, 101b etc.). Like individual comb fingers 100a, 100b, etc. are electrically connected by connection element 100. Similarly, like individual comb fingers 101a, 101b, etc. are electrically connected by connection element 101. In this embodiment, comb-fingers 100a, 100b, 101a, 101b, and connection elements 100 and 101 are formed



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from a conductive material. To obtain a nonzero force for quadrature-error cancellation, the gaps separating comb finger sets must not equal the gap between comb-fingers within a single set, i.e. $Y_1$, the distance to the next set, should not equal $Y_2$. Typically, the ratio of these gaps differ by a factor of two or more in either direction, i.e. $Y_2 > 2Y_1$ or $Y_1 > 2Y_2$.

Note when multiple fingers are needed to provide sufficient quadrature-correcting force, like fingers may be connected to the same electrical node. Thus, like fingers (for example, 100a and 100b) may be formed in a single layer of conducting material. Finger(s) 100a (100b etc.) may be attached to a proof-mass and finger(s) 101a (101b etc.) may be attached to the substrate. Alternatively, finger(s) 100a (100b etc.) may be attached to the substrate and finger(s) 101a (101b etc.) may be attached to a proof-mass. A quadrature-nulling force, with Y-axis value having a component proportional to X-axis displacement, is generated by applying a voltage V between the two electrical nodes formed by like interconnected fingers. When multiple sets of cancellation fingers are required, the Y-axis force on a single finger 101a for a single finger pair located adjacent to another finger pair is approximately:

$$F_Y(x) = \frac{\varepsilon_0 Z_1 x}{2}\left(\frac{1}{Y_2^2} - \frac{1}{Y_1^2}\right)V^2 = \underbrace{\frac{\varepsilon_0 Z_1 X_1}{2}\left(\frac{1}{Y_2^2} - \frac{1}{Y_1^2}\right)V^2}_{Static\,Force} - \underbrace{\frac{\varepsilon_0 Z_1 dx}{2}\left(\frac{1}{Y_2^2} - \frac{1}{Y_1^2}\right)V^2}_{Force\,Proportional\,to\,Displacement}$$

Equation 5

where $X_1$, and $Z_1$ are the nominal overlap lengths of the quadrature-nulling structure in the X- and Z-directions, $\varepsilon_0$ is the permittivity of free space, $Y_2$ is the nominal separation distance between comb-finger 100a and comb-finger 101a, $Y_1$ is the nominal separation distance between comb-finger 101a and comb-finger 100b (i.e. the next comb-finger set), and $dx$ is the displacement of the end of comb-finger 101a from the nominal position along the X-direction - the overlap length along the X-direction at a given displacement $dx$ being equal to $X_1$-$dx$. Typically the fingers comprise a conductive material, such as doped silicon or doped polysilicon, having a thickness $Z_1$ from about 2 microns to 100 microns, a width $t_y$ from about 1 to 25 microns, a finger length $t_x$ from about 2 to 50 microns, and an overlap length $X_1$ of more than 2 microns. The gap distance $Y_2$ is typically between 1 to 10 microns with $Y_1$ typically being 2 or more times $Y_2$. The actual dimensions of the quadrature-nulling structures will, of course, depend on the specificities of both the particular mechanical design as well as the particular technology in which the structures are formed. Examples of parameters that may affect the quadrature-nulling structure dimensions include: the amount of quadrature-nulling required by a particular mechanical design; the uniformity and sidewall angle of suspensions and beams used in the construction of a sense-element; minimum definable line or space set by photolithographic constraints (i.e. critical dimension); and residual stress gradient in a film into which a sense-element is formed.

From Equation 5 it is clear that if $Y_1$ is set equal to $Y_2$ then the resulting quadrature-correction force, the component of force proportional to



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displacement, is zero: $F_y$ is independent of displacement along the X-direction. When $Y_1$ is not equal to $Y_2$, $F_y$ is a function of relative X-axis displacement, and correspondingly appears as an off diagonal element when represented in spring matrix form. Since this spring-force may be adjusted by voltage $V$, it may be used to cancel off-axis spring terms due to, for instance, imperfections in the suspension. An important advantage of the present invention may now be noted. When the comb-finger capacitors comprise a conductive material, and the voltage across the comb-finger capacitor is provided by a low-impedance voltage source, such as the output of an operational amplifier connected in negative feedback, or a electrochemical battery, there is essentially zero phase error between proof-mass position along the drive-axis and the force $F_y$. An in-phase relationship between these two quantities enables effective cancellation of off-diagonal terms in the spring-matrix, thereby providing improved oscillation.

Figure 5A illustrates a schematic diagram of a second embodiment of the invention. A single-mass gyroscope includes a quadrature-nulling structure comprising comb fingers 200a, 200b anchored to substrate 250 and proof-mass comb finger 201a, connected to proof-mass 210. Proof-mass 210 is suspended above substrate 250 by a suspension that may be decomposed into substantially orthogonal springs 221 and 222. This schematic diagram shows proof-mass motion with quadrature-error which is hereby denoted as positive, since the proof-mass moves along the positive Y-axis for proof-mass motion along the positive X-axis. The arrow on the proof-mass represents



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motion of the proof-mass under zero input rate: largely along the X-axis, or drive-axis, with a small component along the Y-axis or sense-axis. Y-axis motion is exaggerated to aid in the description of the invention. Application of a voltage between comb-fingers 201a and comb-finger 200a, 200b may be used to provide a X-axis dependent force to proof-mass 210 having a Y-axis component shown in Equation 5. This Y-axis force, directed in the positive Y-direction, may be adjusted to result in a zero dynamic Y-axis displacement during motion along the X-axis, as shown in Figure 5B. Note that since electrostatic forces across a capacitor are attractive, this embodiment of the invention is unable to cancel negative quadrature-errors because the gap between finger 200a and 201a is smaller than the gap between 200b and 201a. Furthermore, note that while dynamic motion is attenuated, a static Y-axis displacement may remain. The presence of a static Y-axis displacement is typically of little consequence, however, since electrical outputs from position-sense circuitry due to static displacement is modulated to higher frequencies when Coriolis acceleration is demodulated.

Since it is often desirable to maintain symmetry in a mechanical sense-element, multiple quadrature-error cancellation structures may be utilized, as shown in a third and fourth embodiment of the invention shown in Figures 6 and 7 respectively. These embodiments have the ability to cancel both positive and negative quadrature-errors. Once again, for clarity, suspension elements, drive-capacitors and sense-capacitors are not shown.



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In a third embodiment of the invention a single-mass gyroscope includes a quadrature-nulling structure comprising anchored comb fingers 300a,b and 302a,b; proof-mass comb fingers 301a and 303a; and proof-mass 310. Figure 6A shows proof-mass motion with negative quadrature-error. The arrow on the proof-mass represents motion of the proof-mass under zero input rate: largely along the X-axis, or drive-axis, with a small component along the Y-axis or sense-axis. Figure 6B shows that application of a voltage between comb-fingers 303a and comb-fingers 302a, 302b may be used to provide a X-axis dependent force to proof-mass 310 having a Y-axis component. This Y-axis force, directed along the positive Y-axis, may be adjusted to result in a zero dynamic Y-axis displacement during motion along the X-axis, as shown in Figure 6B. Note that separate, independent voltages may be applied across both capacitors: the capacitor formed by fingers 300a, 300b and 301a, and the capacitor formed by fingers 302a, 302b and 303a. In this manner, voltages may be applied across both sets of capacitors to provide a biased operating point about which quadrature-error may be canceled. Operation about a biased operating point may be advantageous when quadrature error is very small, fluctuates between positive and negative, or a linear voltage to force relationship is desired.

While the third embodiment of the invention provides for cancellation of positive and negative quadrature-error, the lack of quadrature-error cancellation structures providing a net electrostatic attraction along the negative Y-axis may cause a static displacement along the Y-axis to occur



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when quadrature-error is canceled via application of voltage to the cancellation structures and under zero rate input. A fourth embodiment of the invention provides for cancellation of positive and negative quadrature-error, while enabling the static component of displacement along the Y-axis to be controlled.

In a fourth embodiment of the invention a single-mass gyroscope includes a balanced quadrature-nulling structure comprising anchored comb fingers 400a, 400b, 402a, 402b, 404a, 404b and 406a, 406b; proof-mass comb fingers 401a, 403a, 405a, and 407a; and proof-mass 410. Figure 7A shows proof-mass motion with positive quadrature-error. The arrow on the proof-mass represents motion of the proof-mass under zero input rate: largely along the X-axis, or drive-axis, with a small component along the Y-axis or sense-axis. Figure 7B shows that application of a voltage between comb-fingers 401a and comb-fingers 400a, 400b in conjunction with application of a voltage between comb-fingers 407a and comb-fingers 406a, 406b may be used to provide a X-axis dependent force to proof-mass 410. The Y-axis forces, may be adjusted to result in both a zero dynamic and a zero static Y-axis displacement during motion along the X-axis, as shown in Figure 7B. Note that this embodiment also provides for the operation about a biased operating point, in which each of the four capacitors include a nonzero voltage component across them: the capacitor formed by fingers 400a, 400b and 401a, the capacitor formed by fingers 402a, 402b and 403a, the capacitor



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formed by fingers 404a, 404b and 405a, and the capacitor formed by fingers 406a, 406b and 407a.

In a fifth embodiment of the invention, shown in Figure 8A, a dual-mass gyroscope includes a quadrature-nulling structure comprising anchored comb fingers 500a, 500b, 502a, 502b; proof-mass comb fingers 501a, 503a; and proof-masses 510a, 510b. In nominal operation, the proof-masses will be driven in an anti-phase manner along the X-axis. Figure 8A shows differential proof-mass motion with quadrature-error which is hereby denoted as positive. The arrows on the proof-masses represent motion of the proof-masses under zero input rate: largely differential or anti-phase motion along the X-axis, or drive-axis, with a small differential component along the Y-axis or sense-axis. Figure 8B shows that application of a voltage between comb-fingers 501a and comb-fingers 500a, 500b may be used to provide a X-axis dependent force to proof-mass 510. The Y-axis force may be adjusted to result in zero differential dynamic Y-axis displacement during motion along the X-axis, as shown in Figure 8B. Note that this embodiment also provides for the operation about a biased operating point. While the fifth embodiment of the invention provides for cancellation of both positive and negative quadrature-error in a dual-mass gyroscope, the lack of quadrature-error cancellation structures providing a net electrostatic attraction along the negative Y-axis may cause a dynamic variation of common-mode displacement with a static differential component along the Y-axis to occur when quadrature-error is canceled via application of voltage to the cancellation structures and under zero rate input.



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In a sixth embodiment of the invention, shown in Figure 9A, a dual-mass gyroscope includes a quadrature-nulling structure comprising anchored comb fingers 600a, 600b, 602a, 602b, 604a, 604b, 606a, 606b; proof-mass comb fingers 601a, 603a, 605a, 607a; and proof-masses 610a,b. In nominal operation, the proof-masses will be driven in an anti-phase manner along the X-axis. Figure 9A shows differential proof-mass motion with positive quadrature-error. The arrows on the proof-masses represent motion of the proof-masses under zero input rate: largely differential motion along the X-axis, or drive-axis, with a small differential component along the Y-axis or sense-axis. Figure 9B shows that voltages may be chosen and applied across the four capacitors formed by the following capacitor pairs: (600a,b; 601a), (602a,b; 603a), (604a,b; 605a), (606a,b; 607a). The voltages may be used to provide X-axis dependent forces along the Y-axis to proof-masses 610a,b. The Y-axis force may be adjusted to result in zero dynamic differential Y-axis displacement and zero dynamic common-mode Y-axis displacement during motion along the X-axis, as shown in Figure 9B. While dynamic common-mode Y-axis displacement may be attenuated, a static common-mode displacement with a static differential component may still remain.

In a seventh embodiment of the invention a dual-mass gyroscope includes a balanced quadrature-nulling structure for each proof-mass, the balanced quadrature-nulling structure being similar to the structure shown in Figure 7A and Figure 7B.



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Note that in these embodiments of the invention, fingers anchored to the substrate of each independent quadrature-nulling structure may be driven to different electrical potentials. In most cases the fingers anchored to the proof-masses will have similar potential with respect to each other; however, this constraint is not necessary to practice the invention.

Figure 10 illustrates a simplified plan-view of a single-mass vibratory rate gyroscope including: a suspension anchored to substrate 720 via anchors 703, a suspension comprising flexures 701, 702, 702a and similar beams; quadrature-cancellation structures 708, 710, 711, and 713; drive-sense 707,714 and drive-force 709,712 interdigitated comb-drive capacitors for oscillating proof-mass 700 along the drive-axis using, for example, a transresistance amplifier (see for example Roessig, T.A., Integrated MEMS Tuning Fork Oscillators for Sensor Applications, University of California, 1998); and a capacitor bridge formed of fingers 704, 705, 706, and similar fingers connected by interconnection 730a,b and contacts 731. Note that finger 705 and similar connected fingers form the center terminal of the capacitor bridge. Imbalance in the capacitive bridge may be detected using any of a number of techniques well-known by those skilled in the art (see for example: Boser, B.E., Howe, R.T., "Surface micromachined accelerometers," IEEE Journal of Solid-State Circuits, vol.31, pp. 366-75, March 1996; M. Lemkin, B.E. Boser, "A three-axis micromachined accelerometer with a CMOS position-sense interface and digital offset-trim electronics," IEEE Journal of Solid-State Circuits, pp. 456-68, April 1999; Sherman, S.J, et. al., "A low cost

monolithic accelerometer; product/technology update," International Electron Devices Meeting, San Francisco, CA, Dec. 1992, pp. 501-4). The sense-element is typically formed in a conductive mechanical device layer, such as doped silicon.

Figure 11 illustrates a schematic diagram of a vibratory rate gyroscope with closed-loop quadrature-error cancellation. The feedback loop operates by measuring quadrature error and adjusting the bias voltages on the quadrature-error cancellation structures in accordance with a filtered representation of the quadrature error. This feedback loop is connected so that the measured quadrature error is driven towards zero. Sense-element 800 includes one or more proof-masses, one or more drive capacitors for providing an oscillation sustaining force along a drive-axis, one or more sense capacitors for detecting displacements of the proof-mass along a sense-axis, one or more suspensions, and a set of quadrature-error cancellation structures. A vibratory-rate gyroscope with closed-loop quadrature-error cancellation comprises sense-element 800; an oscillation sustaining feedback network 801 including a connection to drive capacitors, the *oscillation* sustaining feedback loop having an output 801a substantially in-phase with proof-mass position; synchronizer 802, having in-phase 808 and quadrature 807 outputs, which may be a phase-locked loop or comparator, synchronizer 802 providing synchronous demodulation signals for mixers 804 and 805; position-sense interface 803 including a connection to sense capacitors; mixer 804 to demodulate the quadrature-error portion of position-sense interface

output 803a to a baseband signal; filter 806 for setting the bandwidth of the quadrature-error cancellation feedback loop; connection 806a from filter 806 to quadrature-error cancellation structures; mixer 805 to demodulate the Coriolis–signal portion of position-sense interface output 803a to a baseband signal; filter 810 for low-pass filtering the demodulated Coriolis signal thereby providing an electrical output representative of an input rotation rate, with suppressed quadrature-error. Since mixer 804 is synchronized with drive-axis position, mixer 804 serves as a quadrature detection circuit.

In an alternative embodiment, oscillation sustaining loop output 801a is substantially in phase with drive-mode velocity. In this case the demodulation signals provided to the two mixers are interchanged to correctly demodulate quadrature and Coriolis acceleration.

The schematic diagram of Figure 11 includes circuit and signal processing elements represented as functional blocks. These functional blocks comprise well-known circuits and devices and are shown in block diagram form to avoid unnecessary distraction from the underlying invention. It is explicitly noted, however, that the functional blocks and feedback connections may operate in a continuous-time fashion, a sampled-data fashion, or a combination thereof.

Some prior-art active quadrature-error correction techniques require multiple electrical nodes closely-spaced adjacent to each other, resulting in increased parasitic capacitance, increased wiring complexity, and increased size. Depending on the technology in which the gyroscope and quadrature-



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nulling structures are formed, the present invention may be highly advantageous because only two electrical nodes are required for each independent quadrature-nulling structure, only one node being anchored to the substrate. Thus, interconnection between like comb-fingers of a quadrature-nulling structure is greatly simplified – especially when fingers are formed in a single-crystal-silicon fabrication technology such as described in (Clark, et al., US Patent Application 09/322,381 filed 5/28/99; Clark, et al., US Provisional Patent Application 60/127,973 filed 4/6/99; Brosnihan, et al., US Patent Application 08/874,568 filed 6/13/97; Diem, et al., US Patent 5,495,761 issued 3/5/96; Offenberg, et al., US Patent 5,627,317 issued 5/6/97; Shaw, et al., US Patent 5,719,073 issued 2/17/98). Simple interconnection may translate to significantly reduced pitch between adjacent quadrature-nulling finger-pairs thereby reducing sensor area. Furthermore, parasitic capacitance between adjacent sets of comb fingers may be reduced, as compared to prior-art quadrature-error cancellation structures (see for example Clark, et al., US Patent 5,992,233 issued 11/30/99; Clark, et al., US Patent Application 09/321,972 files 5/28/99) leading to improved electrical characteristics when the quadrature-error cancellation structures are included in a feedback loop that measures the quadrature error and adjusts bias voltages accordingly. Furthermore, parasitic capacitance can slow settling and stability of voltages applied across quadrature-cancellation structures, thereby introducing a phase error between proof-mass position along the drive-axis and the force $F_y$.



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The invention has been described as being especially advantageous when the structures are formed in a single-crystal-silicon fabrication technology. However, it is not necessary to form structures in a single-crystal silicon technology to practice the invention. The invention may be co-fabricated with integrated circuitry on a single chip using many fabrication methods including, but not limited to: surface micromachining, reactive ion etching, SOI-based micromachining, epi-polysilicon micromachining, or similar fabrication methods or technologies. Examples of some applicable fabrication technologies may be found in, for example: U.S. Provisional Patent Application Serial Number 60/127,973, filed 4/6/1999; U.S. Patent Application Serial Number 09/322,381, filed 5/28/1999; and US Patents: Tsang, et al., US patent number 5,326,726, issued 7/5/94; Spangler, et al., US patent number 5,343,064, issued 8/30/94; Bashir, et al., US patent number 5,747,353, issued 5/5/98; Montague, et al., US patent number 5,798,283, issued 8/25/98; Zhang, et al., US patent number 5,506,175 issued 4/9/96; Kung, US patent number 5,504,026, issued 4/2/96.

Alternatively, different components comprising the invention may be formed as discrete elements. For example, the sense element may be formed on a silicon or quartz substrate and the interface, control and signal processing circuitry may be formed on one or more separate substrates as described in, for example: U.S. Patents: MacDonald, et al., US patent number 5,198,390, issued 3/30/93; Diem, et al., US patent number 5,576,250, issued 11/19/96; Field, et al., US patent number 5,882,532, issued 3/16/99; Smith, T.



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et. al., "A 15b Electromechanical Sigma-Delta Converter for Acceleration Measurements," ISSCC Dig. Tech. Papers, pp. 160-161, 1994. Alternatively, the sense-element may be bulk-micromachined by any of a number of well-known methods, interface, control and signal processing circuitry may be formed on one or more separate substrates, and the electrical and mechanical substrates may be connected by one or more wire bonds.

The foregoing description, for the purposes of explanation, used specific nomenclature to provide a thorough understanding of the invention. However, it will be apparent to one skilled in the art that the specific details are not required in order to practice the invention. Thus, the foregoing descriptions of specific embodiments of the invention are presented for the purposes of illustration and description. They are not intended to be exhaustive or to limit the invention to the precise forms disclosed, obviously many modifications and variations are possible in view of the above teachings. For example, the invention may be used to obtain improved performance in single-mass frame-based or dual-mass frame-based gyroscopes, such as those described in (Geen, J., “A path to low cost gyroscopy,” IEEE Solid-State Sensor and Actuator Workshop, Hilton Head Island, SC, June 8 - 11,1998, pp 51-4; Schumacher, K. et al., “Micromechanical Liga-Gyroscope”, Transducers 99, June 7-10 Sendai Japan, pp 1574-1577.), by providing improved drive-axis oscillation. The quadrature-error cancellation structures may also be used to adjust a compliant mode in a non-vibrating microstructure, such as an accelerometer, so that the compliant mode more accurately aligns with a



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predetermined direction – providing improved package alignment, for example. The embodiments were chosen and described in order to best explain the principles of the invention and its practical applications, to thereby enable others skilled in the art to best utilize the invention and various embodiments with various modifications as are suited to the particular use contemplated.

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## CLAIMS

What is claimed is:

1. A movable microstructure comprising:

a first finger set comprising at least two first fingers extending substantially parallel to a first displacement axis;

a second finger set comprising at least one second finger, said at least one second finger extending substantially parallel to said first displacement axis, terminating between two first fingers, wherein each second finger is substantially closer to one of the two first fingers between which it terminates; and

an electrical circuit providing a position-dependent force having a magnitude varying in proportion to displacement along said first displacement axis.

2. The movable microstructure of claim 1 wherein said at least two first fingers comprise a conductive material, having a thickness between 2 and 100 microns, a width between 1 and 25 microns, a finger length between 2 to 50 microns, and an overlap length of more than 2 microns.

3. The movable microstructure of claim 2 wherein said at least one second finger comprises a conductive material, having a thickness between 2 and 100 microns, a width between 1 and 25 microns, a finger length between 2 to 50 microns, and an overlap length of more than 2 microns.

4. A movable microstructure comprising:

a substrate;

a proof-mass disposed above said substrate;

a first finger set comprising two or more first fingers affixed to said substrate and extending substantially parallel to a first displacement axis towards said proof-mass;

a second finger set comprising at least one second finger, each member of the second finger set extending substantially parallel to said first displacement axis from said proof-mass, terminating between two first fingers, wherein each second finger is substantially closer to one of the two first fingers between which it terminates, thereby forming a first capacitor; and

an electrical circuit providing a voltage across said capacitor to provide a position-dependent force on said proof-mass, said position-dependent force having a component along an axis substantially orthogonal to said first displacement axis, the magnitude of said position-dependent force varying in proportion to displacement along said first displacement axis.

5. The movable microstructure of claim 4 further including an oscillation-sustaining feedback loop having an output representative of proof-mass movement along said first displacement axis, said oscillation-sustaining feedback loop using electrostatic forces to sustain oscillatory motion.



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6. The movable microstructure of claim 5 further including:

a capacitive bridge responsive to displacements of said proof-mass along an axis orthogonal to said first displacement axis; and

a position sense interface connected to said capacitive bridge, said position sense interface having an electrical output varying in response to changes in said capacitive bridge.

7. The movable microstructure of claim 5 wherein the voltage applied to said first capacitor is substantially constant and chosen to cause said vibrating mass, absent a Coriolis force, to vibrate more precisely along said first axis.

8. The movable microstructure of claim 6 further including:

a quadrature detection circuit having an output, said quadrature detection circuit synchronized with the output of said oscillation-sustaining feedback loop; and

a feedback connection from the output of said quadrature detection circuit to said first capacitor, said feedback connection providing a voltage across said first capacitor;

wherein said voltage causes the average output of said quadrature detection circuitry to converge towards a constant value, thereby causing said mass to vibrate, absent a Coriolis force, more precisely along said first axis.

9. The movable microstructure of claim 4 further including:

a third finger set comprising two or more third fingers affixed to said substrate and extending substantially parallel to a first displacement axis towards said proof-mass; and

a fourth finger set comprising at least one fourth finger, each member of the fourth finger set extending substantially parallel to said first displacement axis from said proof-mass along a direction opposite the direction of extension of said second fingers, terminating between two third fingers, wherein each fourth finger is closer to one of the two third fingers between which it terminates, thereby forming a second capacitor.

10. The moveable microstructure of claim 9 wherein said electrical circuit provides a voltage across said second capacitor to provide a position-dependent force on said proof-mass, said position-dependent force having a component along an axis substantially orthogonal to said first displacement axis, the magnitude of said position-dependent force varying in proportion to displacement along said first displacement axis.

11. The moveable microstructure of claim 9 further including an electrical circuit providing a voltage across said second capacitor to provide a position-dependent force on said proof-mass, said position-dependent force having a component along an axis substantially orthogonal to said first displacement axis, the magnitude of said position-dependent force varying in proportion to displacement along said first displacement axis.

12. The movable microstructure of claim 9 further including:

a capacitive bridge responsive to displacements of said proof-mass along a sense axis orthogonal to said first displacement axis;

a position sense interface connected to said capacitive bridge, said position sense interface having an electrical output varying in response to changes in said capacitive bridge;

a quadrature detection circuit having an output, said quadrature detection circuit synchronized with the output of said oscillation-sustaining feedback loop;

a feedback connection from the output of said quadrature detection circuit to said first and second capacitors, said feedback connection providing a defined voltage across each of said first and second capacitors, said voltage causing the average output of said quadrature detection circuitry to converge towards a constant value, thereby causing said mass to vibrate, absent a Coriolis force, more precisely along said first axis; and

a Coriolis detection circuit having an output, said Coriolis detection circuit synchronized with the output of said oscillation-sustaining feedback loop;

wherein the Coriolis detection circuit output provides an electrical signal representative of rotational motion about an axis largely orthogonal to both said sense axis and said first displacement axis.

13. A movable microstructure comprising:

a substrate;

a first proof-mass disposed above said substrate;

a second proof-mass disposed above said substrate;

a first finger set comprising two or more first fingers affixed to said substrate and extending substantially parallel to a first displacement axis towards said first proof-mass;

a second finger set comprising at least one second finger, each member of the second finger set extending substantially parallel to said first displacement axis from said first proof-mass, terminating between two first fingers, wherein each second finger is closer to one of the two first fingers between which it terminates, thereby forming a first smaller gap and a first capacitor;

a third finger set comprising two or more third fingers affixed to said substrate and extending in a direction opposite said first finger set and substantially parallel to said first displacement axis towards said second proof-mass;

a fourth finger set comprising at least one fourth finger, each member of the fourth finger set extending substantially parallel to said first displacement axis from said second proof-mass, along a direction opposite said second fingers, terminating between two third fingers, wherein each fourth finger is closer to one of the two third fingers between which it



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terminates, thereby forming a second smaller gap and a second capacitor; and

an electrical circuit providing a first voltage across said first capacitor, and a second voltage across said second capacitor to provide position-dependent forces on said first proof-mass and on said second proof-mass, said position-dependent forces having a component along an axis substantially orthogonal to said first displacement axis, the magnitude of said position-dependent force varying in proportion to proof-mass displacement along said first displacement axis.

14. The movable microstructure of claim 13 further including an oscillation-sustaining feedback loop having an output representative of the relative movement between said first proof-mass and said second proof-mass along said first displacement axis, said oscillation-sustaining feedback loop using electrostatic forces to sustain oscillatory motion.

15. The movable microstructure of claim 14 further including:

a capacitive bridge responsive to the relative displacement between said first proof-mass and said second proof-mass along an axis orthogonal to said first displacement axis; and

a position sense interface connected to said capacitive bridge, said position sense interface having an electrical output varying in response to changes in said capacitive bridge.

16. The movable microstructure of claim 14 wherein said first voltage and said second voltage are distinct, are substantially constant, and are chosen to cause said vibrating mass, absent a Coriolis force, to vibrate more precisely along said first axis.

17. The movable microstructure of claim 15 further including:

a quadrature detection circuit having an output, said quadrature detection circuit synchronized with the output of said oscillation-sustaining feedback loop; and

a feedback connection from the output of said quadrature detection circuit to said first capacitor and said second capacitor, said feedback connection providing said first voltage and said second voltage;

wherein said first voltage and said second voltage cause the average output of said quadrature detection circuitry to converge towards a constant value, thereby causing said mass to vibrate, absent a Coriolis force, more precisely along said first axis.

18. The movable microstructure of claim 14 further including:

a fifth finger set comprising two or more fifth fingers affixed to said substrate and extending substantially parallel to a first displacement axis towards said first proof-mass in the direction of said first fingers;

a sixth finger set comprising at least one sixth finger, each member of the sixth finger set extending substantially parallel to said first displacement axis from said first proof-mass along the direction of extension of said second fingers, terminating between two fifth fingers, wherein each sixth finger is substantially closer to the fifth finger opposite in direction of said first smaller gap in relation to said second finger, thereby forming a third capacitor;

a seventh finger set comprising two or more seventh fingers affixed to said substrate and extending substantially parallel to a first displacement axis and towards said second proof-mass;

an eighth finger set comprising at least one eighth finger, each member of the eighth finger set extending substantially parallel to said first displacement axis from said second proof-mass opposite the direction of the second fingers, terminating between two seventh fingers, wherein each eighth finger is substantially closer to the seventh finger opposite in direction of said second smaller gap in relation to said fourth finger, thereby forming a fourth capacitor; and

an electrical circuit providing a third voltage across said third capacitor, and a fourth voltage across said fourth capacitor to provide position-dependent forces on said first proof-mass and on said second proof-mass, said position-dependent forces having a component along an axis substantially orthogonal to said first displacement axis, the magnitude of said position-dependent force varying in proportion to proof-mass displacement along said first displacement axis.

19. The movable microstructure of claim 18 further including:

a capacitive bridge responsive to the relative displacement between said first proof-mass and said second proof-mass along an axis orthogonal to said first displacement axis;

a position sense interface connected to said capacitive bridge, said position sense interface having an electrical output varying in response to changes in said capacitive bridge;

a quadrature detection circuit having an output, said quadrature detection circuit synchronized with the output of said oscillation-sustaining feedback loop;

a feedback connection from the output of said quadrature detection circuit to said first capacitor, said second capacitor, said third capacitor and said fourth capacitor, said feedback connection providing said first voltage, said second voltage, said third voltage and said fourth voltage; and

a Coriolis detection circuit having an electrical signal output representative of rotational motion about an axis largely orthogonal to both said sense axis and said first displacement axis, said Coriolis detection circuit synchronized with the output of said oscillation-sustaining feedback loop.

20. A micromachined vibratory rate gyroscope comprising:

a substrate;

a proof-mass disposed above said substrate;

a first finger set comprising two or more first fingers affixed to said substrate and extending substantially parallel to a first displacement axis towards said proof-mass;

a second finger set comprising at least one second finger, each member of the second finger set extending substantially parallel to said first displacement axis from said proof-mass, terminating between two first fingers, wherein each second finger is substantially closer to one of the two first fingers between which it terminates, thereby forming a capacitor;

an oscillation-sustaining feedback loop having an output representative of proof-mass movement along said first displacement axis;

a capacitive bridge responsive to displacements of said proof-mass along an axis orthogonal to said first displacement axis;

a position sense interface connected to said capacitive bridge, said position sense interface having an electrical output varying in response to changes in said capacitive bridge;

a quadrature detection circuit having an output, said quadrature detection circuit synchronized with the output of said oscillation-sustaining feedback loop; and

a feedback connection from the output of said quadrature detection circuit to said capacitor, said feedback connection providing a voltage across said first capacitor;

wherein the voltage applied to said capacitor drives the output of said quadrature detection circuitry towards a constant value, thereby causing said mass to vibrate absent a Coriolis force, more precisely along said first axis.

## ABSTRACT

A movable microstructure includes a first finger set comprising two or more first fingers affixed to a substrate and extending substantially parallel to a defined displacement axis towards a proof-mass. The movable microstructure further includes a second finger set comprising at least one second finger, each member of the second finger set extending substantially parallel to the displacement axis from the proof-mass, terminating between two first fingers. Each second finger is substantially closer to one of the two first fingers between which it terminates. The first finger set, in conjunction with the second finger set, form two terminals of a capacitor. An electrical circuit is included that provides a voltage across the capacitor to generate a position-dependent force, the position-dependent force having a component along an axis substantially orthogonal to the displacement axis, the magnitude of the position-dependent force varying in proportion to displacement along the displacement axis.

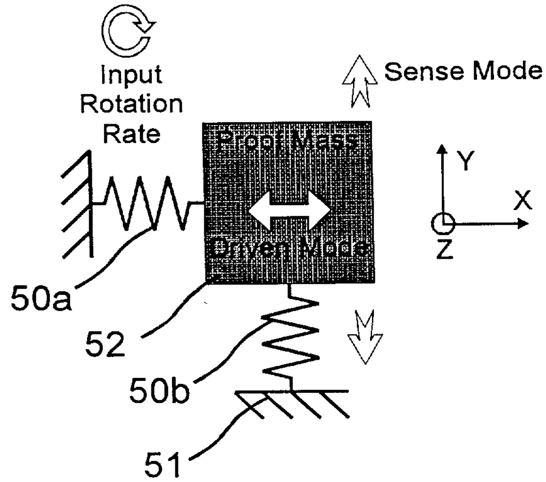


**Figure 1**

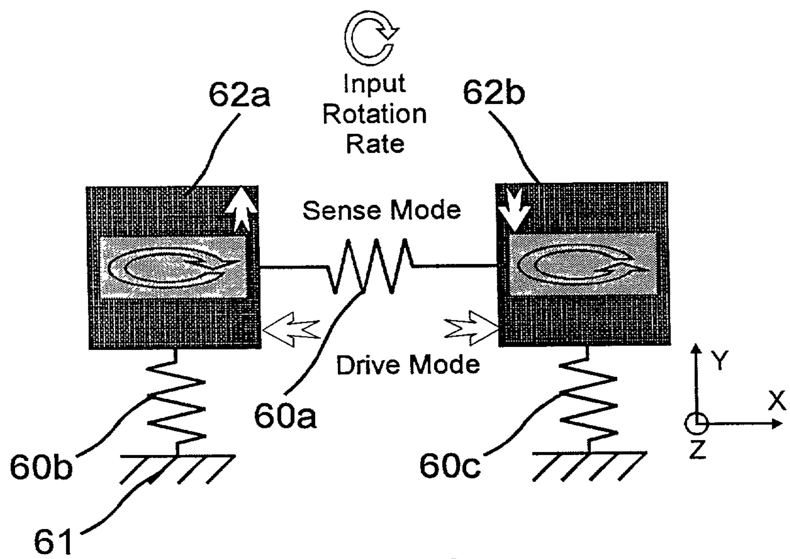


**Figure 2**

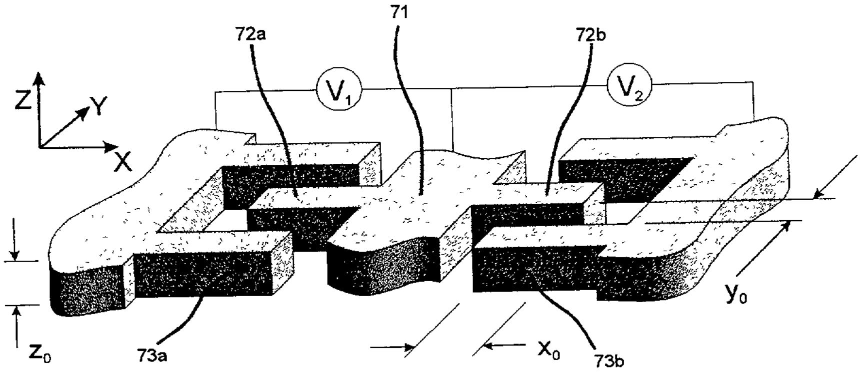


**Figure 3**

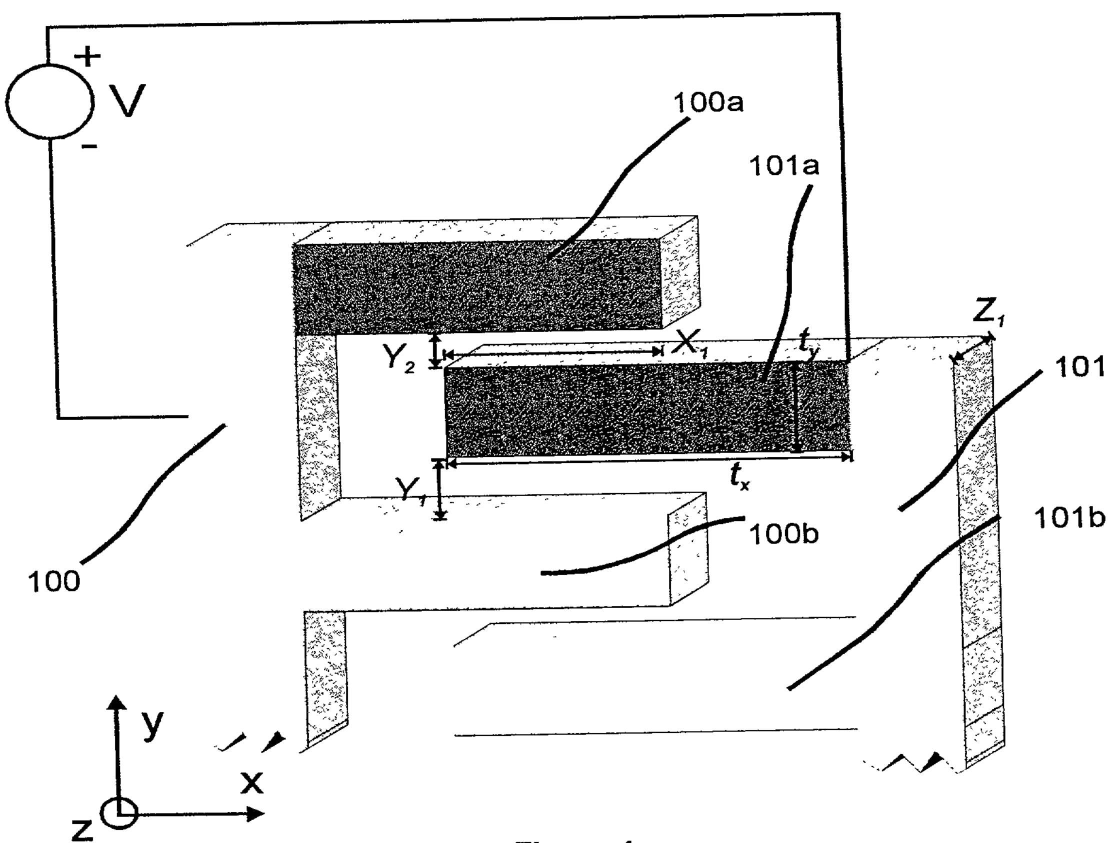


**Figure 4**

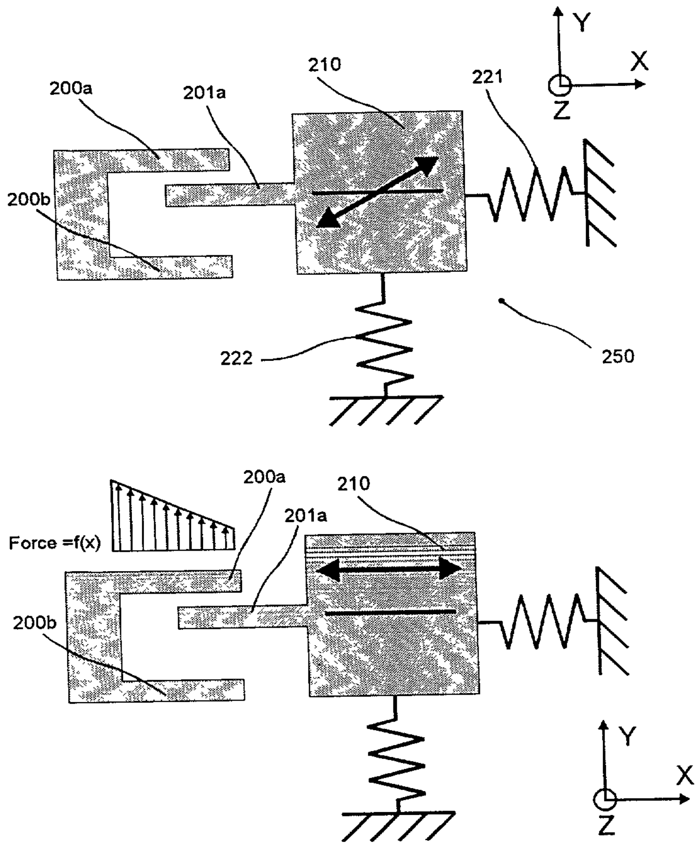


Figure 5: (A) top, (B) bottom.

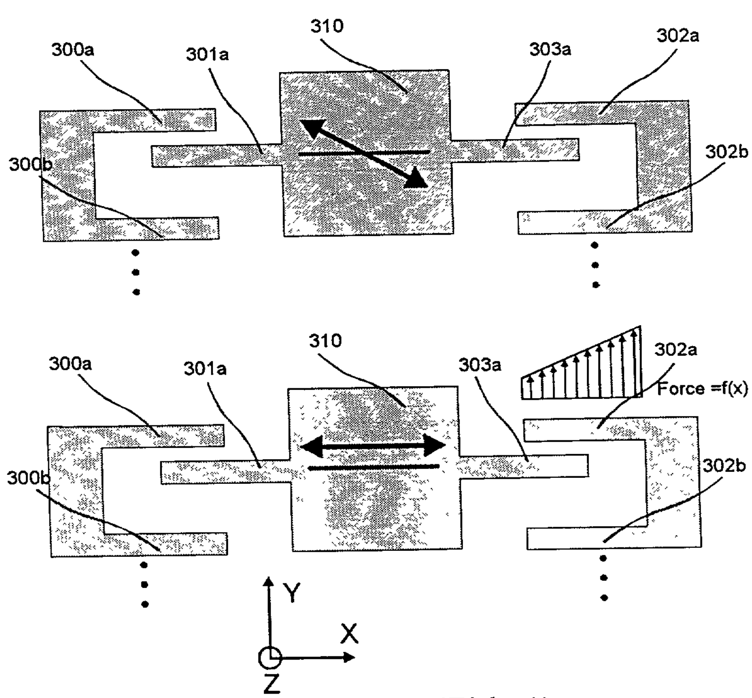


Figure 6: (A) top, (B) bottom.

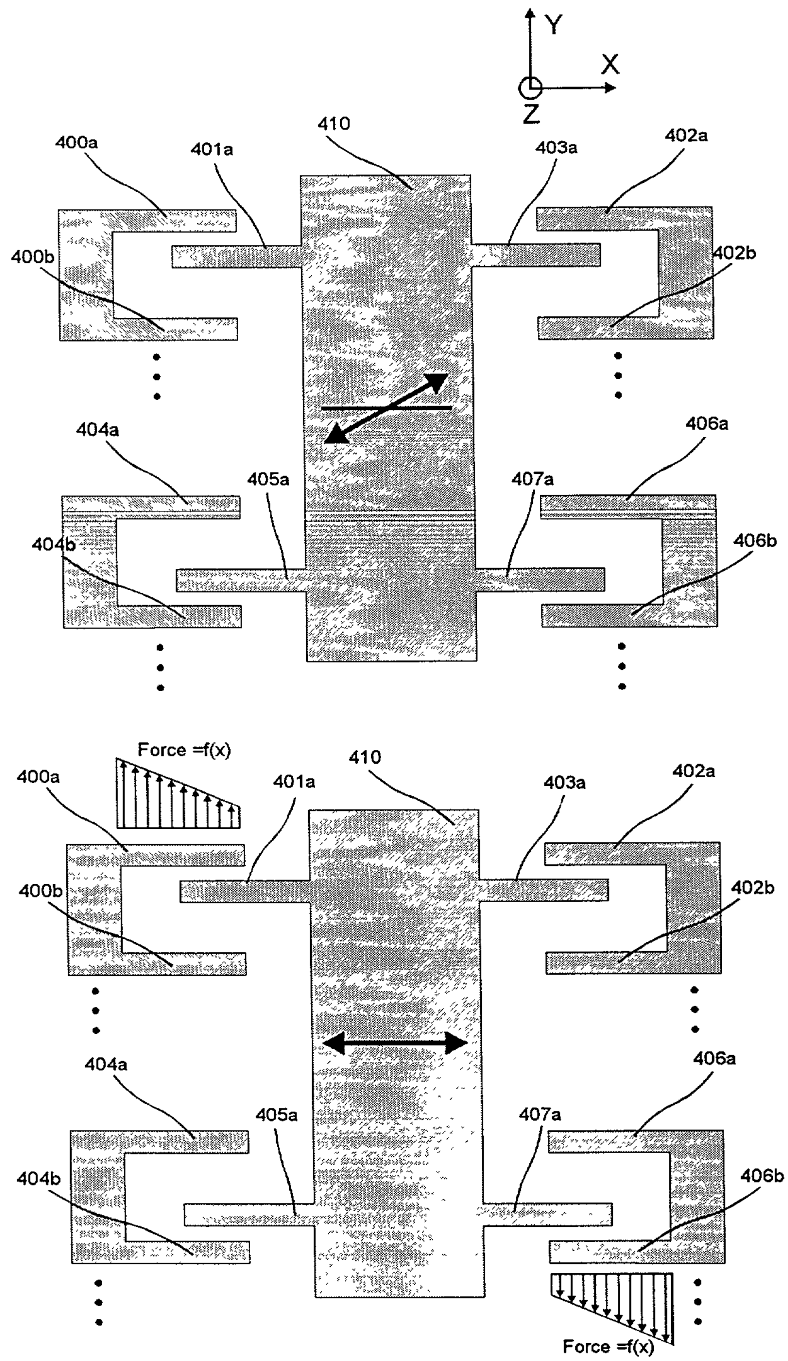


**Figure 7: (A) top, (B) bottom.**

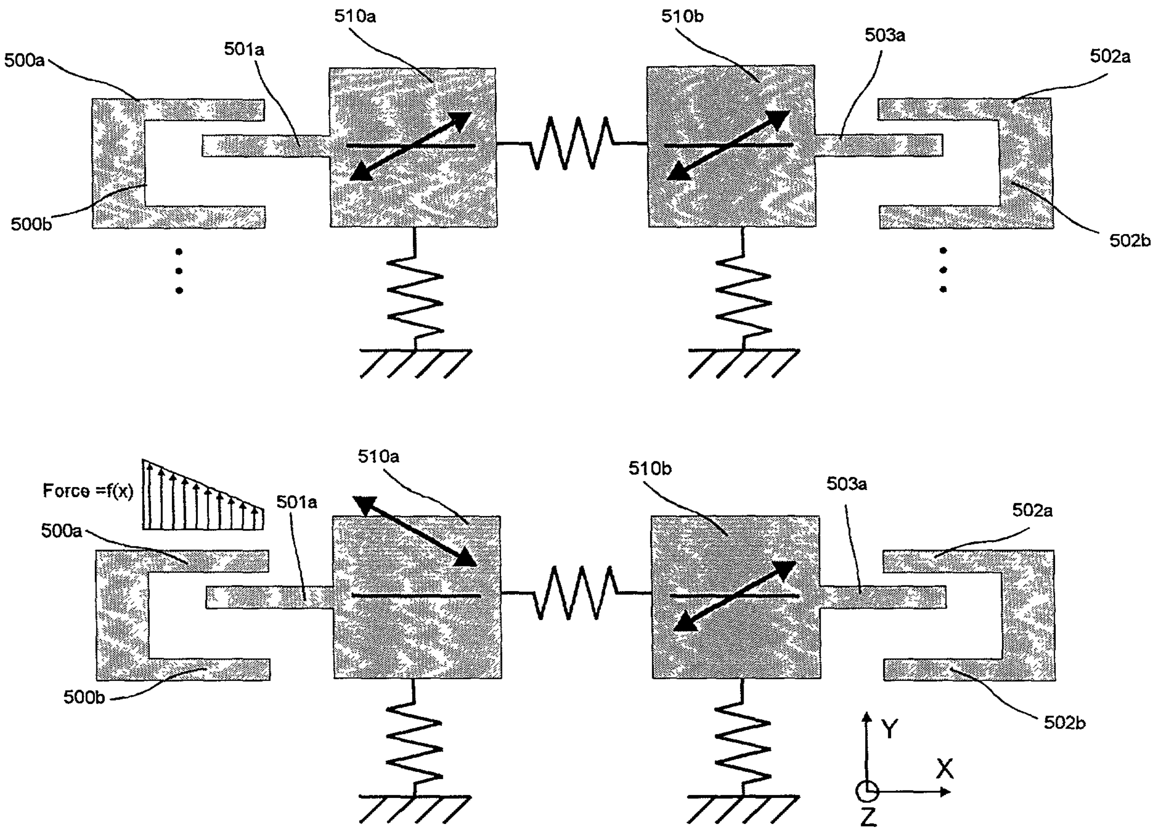


**Figure 8: (A) top, (B) bottom.**

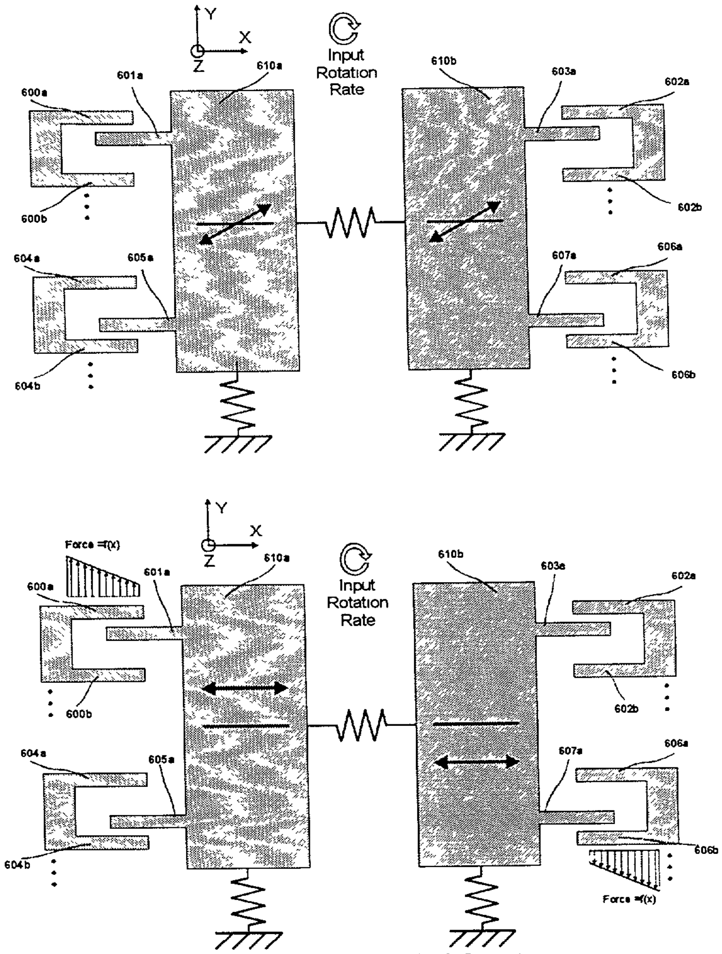


**Figure 9: (A) top, (B) bottom.**

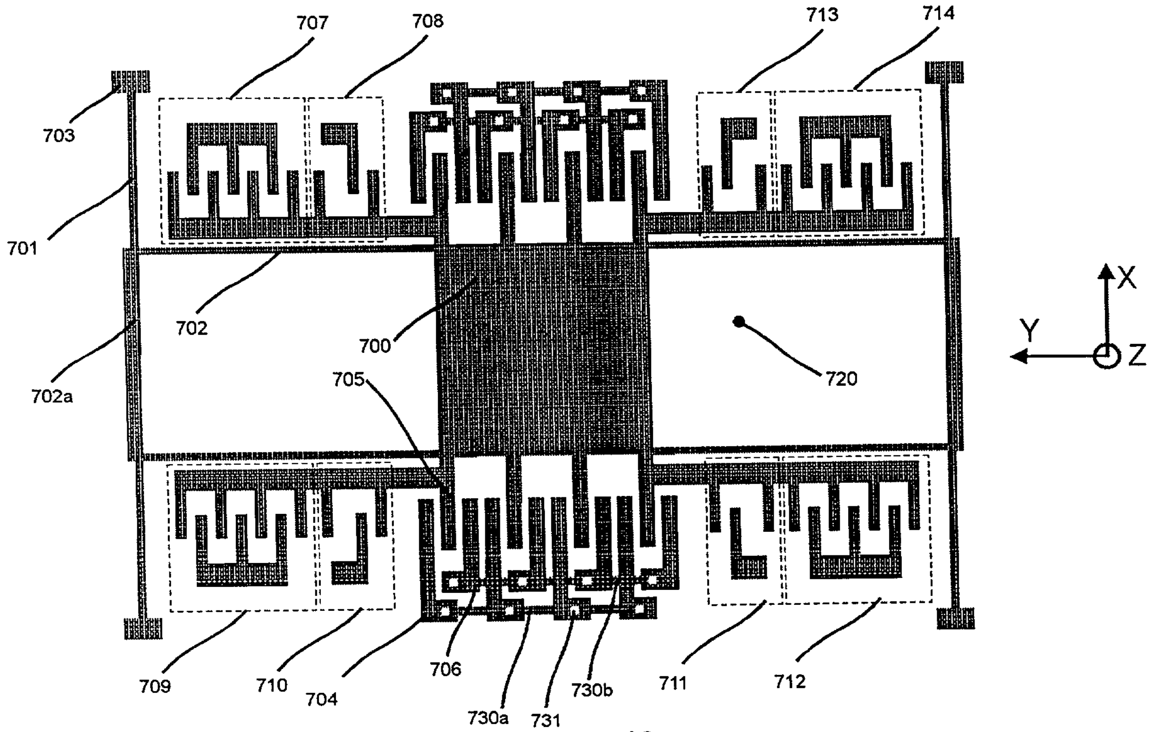


**Figure 10**

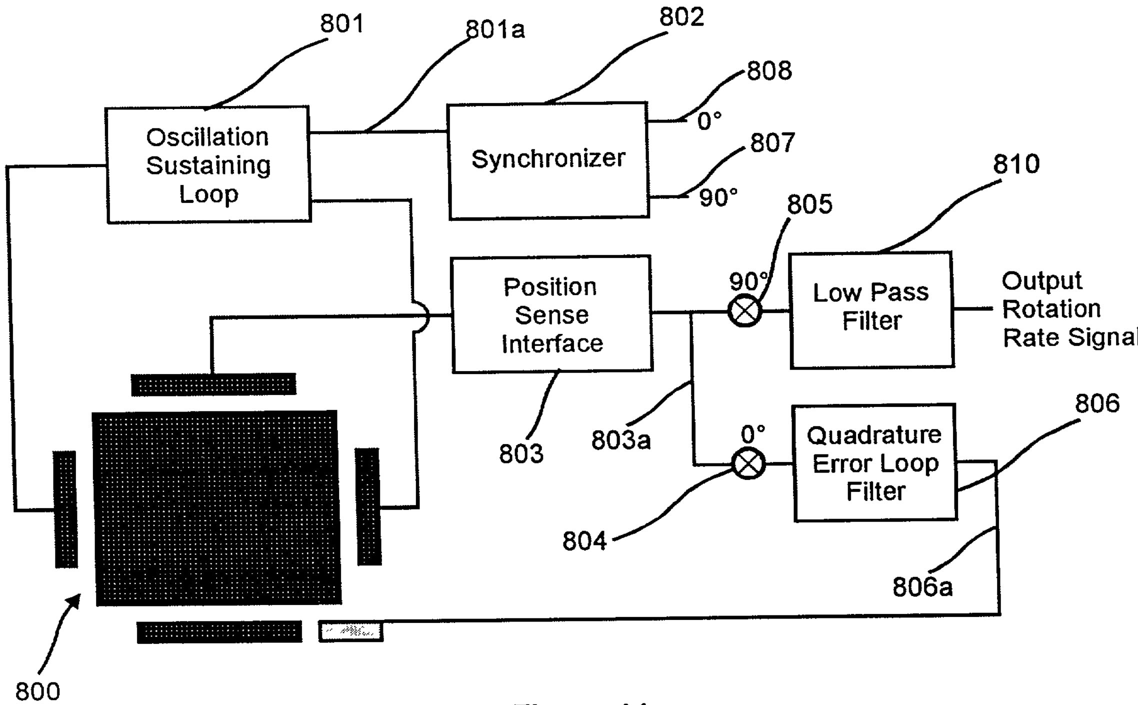


**Figure 11**

JC821 U.S. PTO
06/13/00

## IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

| | | |
|---|---|---|
| In re Application | | ) PATENT APPLICATION |
| Inventor(s): | Lemkin, et al. | ) |
| SC/Serial No.: | Unknown | ) |
| Filed: | Herewith | ) |
| Title: | STRUCTURE FOR ATTENUATION OR CANCELLATION OF QUADRATURE ERROR | ) |

## DECLARATION FOR PATENT APPLICATION

09593593 .061300

As a below named inventor, I hereby declare that my residence, post office address and citizenship are as stated below next to my name; I believe that I am the original, first and sole inventor (if one name is listed below), first and joint inventor (if plural names are listed below) of the subject matter which is claimed and for which a patent is sought on the invention entitled:

STRUCTURE FOR ATTENUATION OR CANCELLATION OF QUADRATURE ERROR

the specification of which (check applicable ones):

__X__ is filed herewith;

______ was filed with the above-identified "Filed" date and "SC/Serial No."

______ was amended on (or amended through) __.

I hereby state that I have reviewed and understand the contents of the above-identified specification, including the claims, as amended by any amendment(s) referred to above. I acknowledge the duty to disclose information which is material to the examination of the application in accordance with Title 37, Code of Federal Regulations, §1.56.

I hereby declare that all statements made herein of my own knowledge are true and that all statements made on information and belief are believed to be true, and further that these statements were made with the knowledge that willful false statements and the like so made are punishable by fine or imprisonment, or both, under §1001 of Title 18 of the United States Code and that such willful false statements may jeopardize the validity of the application or any patent issuing thereon.

(1) Full name of sole
or first inventor: Mark A. Lemkin

(1) Residence: 7450 Terrace Drive
El Cerrito, California 94530

(1) Post Office Address: Same as above

(1) Citizenship: United States

(1) Inventor's signature:

(1) Date: 5/22/00

*****************************************************

(2) Full name of second
joint inventor: William A. Clark

(2) Residence: 35624 Terrace Drive
Fremont, California 94536

(2) Post Office Address: Same as above

(2) Citizenship: United States

(2) Inventor's signature:

(2) Date: 5-22-00

*****************************************************

(3) Full name of third
joint inventor: Thor N. Juneau

(3) Residence: 1812 Delaware Street, #201
Berkeley, California 94703

(3) Post Office Address: Same as above

(3) Citizenship: United States

(3) Inventor's signature:

(3) Date: 5/22/00

*******************************************************

(4) Full name of fourth
joint inventor: Allen W. Roessig

(4) Residence: 37250 Sequoia Terrace, #2030
Fremont, California 94536

(4) Post Office Address: Same as above

(4) Citizenship: United States

(4) Inventor's signature: [signature]

(4) Date: 5/22/00

*******************************************************

**************************************************************

<u>Title 37, Code of Federal Regulations, §1.56</u>

## SECTION 1.56. DUTY TO DISCLOSE INFORMATION MATERIAL TO PATENTABILITY

(a) A patent by its very nature is affected with a public interest. The public interest is best served, and the most effective patent examination occurs when, at the time an application is being examined, the Office is aware of and evaluates the teachings of all information material to patentability. Each individual associated with the filing and prosecution of a patent application has a duty of candor and good faith in dealing with the Office, which includes a duty to disclose to the Office all information known to that individual to be material to patentability as defined in this section. The duty to disclose information exists with respect to each pending claim until the claim is cancelled or withdrawn from consideration, or the application becomes abandoned. Information material to the patentability of a claim that is cancelled or withdrawn from consideration need not be submitted if the information is not material to the patentability of any claim remaining under consideration in the application. There is no duty to submit information which is not material to the patentability of any existing claim. The duty to disclose all information known to be material to patentability is deemed to be satisfied if all information known to be material to patentability of any claim issued in a patent was cited by the Office or submitted to the Office in the manner prescribed by §§1.97(b)-(d) and 1.98.* However, no patent will be granted on an application in connection with which fraud on the Office was practiced or attempted or the duty of disclosure was violated through bad faith or intentional misconduct. The Office encourages applicants to carefully examine:

(1) prior art cited in search reports of a foreign patent office in a counterpart application, and

(2) the closest information over which individuals associated with the filing or prosecution of a patent application believe any pending claim patentably defines, to make sure that any material information contained therein is disclosed to the Office.

(b) Under this section, information is material to patentability when it is not cumulative to information already of record or being made of record in the application, and

(1) It establishes, by itself or in combination with other information, a prima facie case of unpatentability of a claim; or

(2) It refutes, or is inconsistent with, a position the applicant takes in:

(i) Opposing an argument of unpatentability relied on by the Office; or

(ii) Asserting an argument of patentability.

A prima facie case of unpatentability is established when the information compels a conclusion that a claim is unpatentable under the preponderance of evidence, burden-of-proof standard, giving each term in the claim its broadest reasonable construction consistent with the specification, and before any consideration is given to evidence which may be submitted in an attempt to establish a contrary conclusion of patentability.

(c) Individuals associated with the filing or prosecution of a patent application within the meaning of this section are:

(1) Each inventor named in the application;

(2) Each attorney or agent who prepares or prosecutes the application; and

(3) Every other person who is substantively involved in the preparation or prosecution of the application and who is associated with the inventor, with the assignee or with anyone to whom there is an obligation to assign the application.

(d) Individuals other than the attorney, agent or inventor may comply with this section by disclosing information to the attorney, agent, or inventor.

* §§1.97(b)-(d) and 1.98 relate to the timing and manner in which information is to be submitted to the Office.

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IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

| | | |
|---|---|---|
| In re Application | | ) PATENT APPLICATION |
| Inventor(s): | Lemkin, et al. | ) |
| SC/Serial No.: | Unknown | ) |
| Filed: | Herewith | ) |
| Title: | STRUCTURE FOR ATTENUATION OR CANCELLATION OF QUADRATURE ERROR | ) |

## POWER OF ATTORNEY BY ASSIGNEE UNDER 37 C.F.R. §§3.71, 3.73(b)

Assistant Commissioner for Patents
Washington, DC 20231

Sir:

The below-identified Assignee is the owner of the entire right, title and interest in the above-identified patent application by virtue of an assignment from the inventor(s).

___ The assignment was recorded in the United States Patent and Trademark Office at Reel ___, Frames ___ - ___, or

X A true copy of the assignment is attached hereto, the original of which is herewith forwarded to the United States Patent and Trademark Office for recording.

The undersigned (whose title is supplied below) is empowered to sign this statement on behalf of the Assignee.

Assignee hereby appoints Larry E. Vierra, Reg. No. 33,809, and other attorneys of FLIESLER, DUBB, MEYER & LOVEJOY LLP, to prosecute this application and transact all business in the United States Patent & Trademark Office connected therewith; said appointment to be to the exclusion of the inventors and the inventors' attorneys in accordance with the provisions of 37 C.F.R. §3.71.

I hereby declare that all statements made herein of my own knowledge are true and that all statements made on information and belief are believed to be true, and further that these statements were made with the knowledge that willful false statements and the like so made are punishable by fine or imprisonment, or both, under §1001 of Title 18 of the United States Code, and that such willful false statements may jeopardize the validity of the application or any patent issuing thereon.

Please address all correspondence to:
Larry E. Vierra
FLIESLER, DUBB, MEYER & LOVEJOY LLP
Four Embarcadero Center, Suite 400
San Francisco, CA 94111-4156

Please direct all telephone calls to:
Larry E. Vierra
(415) 362-3800

Assignee: Integrated Micro Instruments, Inc.

Assignee Type: Corporation

Signor's Name: Mark A. Lemkin

Signor's Title: Vice President

Signature: Mark A. Lemkin Date: 5/22/00

Attorney Docket No.: IMIN-01005US1
lev/imin/1005.006.wpd

103.001:120197
05/11/0-15:12

# JOINT TO CORPORATE ASSIGNMENT

WHEREAS, the undersigned Inventors:

(1) Mark A. Lemkin,
a resident of 7450 Terrace Drive, El Cerrito, California 94530; and

(2) William A. Clark,
a resident of 35624 Terrace Drive, Fremont, California 94536; and

(3) Thor N. Juneau,
a resident of 1812 Delaware Street #201, Berkeley, California 94703; and

(4) Allen W. Roessig,
a resident of 37250 Sequoia Terrace, #2030, Fremont, California 94536,

have invented certain new and useful improvements in:

STRUCTURE FOR ATTENUATION OR CANCELLATION OF QUADRATURE ERROR

and have executed a declaration or oath for an application for a United States patent disclosing and identifying the invention:

X On the Date of Execution of Declaration for Patent Application set forth below adjacent to my signature.

WHEREAS Integrated Micro Instruments, Inc. (hereinafter termed "Assignee"), a corporation of the State of California, having a place of business at 2140 Shattuck Avenue, Berkeley, State of California, wishes to acquire the entire right, title and interest in and to said application and the invention disclosed therein, and in and to all embodiments of the invention, heretofore conceived, made or discovered jointly or severally by said Inventors (all collectively hereinafter termed "said invention"), and in and to any and all patents, certificates of invention and other forms of protection thereon (hereinafter termed "patents") applied for or granted in the United States and/or other countries.

NOW THEREFORE, for good and valuable consideration acknowledged by each of said Inventors to have been received in full from said Assignee:

1. Said Inventors do hereby sell, assign, transfer and convey to said Assignee, the entire right, title and interest (a) in and to said application and said invention; (b) in and to all rights to apply in any or all countries of the world for patents, certificates of inventions or other governmental grants on said invention, including the right to apply for patents pursuant to the International Convention for the Protection of Industrial Property or pursuant to any other convention, treaty, agreement or understanding; (c) in and to any and all applications filed and any and all patents, certificates of inventions or other governmental grants granted on said invention in the United States or any other country, including each and every application filed and each and every patent granted on any application which is a division, substitution, or continuation of any of said applications; (d)

in and to each and every reissue or extension of any of said patents; and (e) in and to each and every patent claim resulting from a reexamination certificate for any and all of said patents.

2. Said Inventors hereby jointly and severally covenant and agree to cooperate with said Assignee to enable said Assignee to enjoy to the fullest extent the right, title and interest herein conveyed in the United States and other countries. Such cooperation by said Inventors shall include prompt production of pertinent facts and documents, giving of testimony, executing of petitions, oaths, specifications, declarations or other papers, and other assistance all to the extent deemed necessary or desirable by said Assignee (a) for perfecting in said Assignee the right, title and interest herein conveyed; (b) for complying with any duty of disclosure; (c) for prosecuting any of said applications; (d) for filing and prosecuting substitute, divisional, continuing or additional applications covering said invention; (e) for filing and prosecuting applications for reissue of any of said patents; (f) for interference or other priority proceedings involving said invention; and (g) for legal proceedings involving said invention and any applications therefor and any patents granted thereon, including without limitation opposition proceedings, cancellation proceedings, priority contests, public use proceedings, reexamination proceedings, compulsory licensing proceedings, infringement actions and court actions; provided, however, that the expense incurred by said Inventors in providing such cooperation shall be paid for by said Assignee.

3. The terms and covenants of this Assignment shall inure to the benefit of said Assignee, its successors, assigns and other legal representatives, and shall be binding upon said Inventors, their respective heirs, legal representatives and assigns.

4. Said Inventors hereby jointly and severally warrant and represent that they have not entered and will not enter into any assignment, contract, or understanding in conflict herewith.

IN WITNESS WHEREOF, the said Inventors have executed this instrument on the date of acknowledgment before the Notary Public as given below and delivered this instrument to said Assignee.

Date of Execution of Declaration for Patent Application: 5/22/00

(1) [signature]
(Inventor's Signature)

State of California )

County of alameda )

On 05/22/00 before me, Usha K. Potter,
(name and title of officer)

personally appeared Mark A. Lemkin, ~~personally known to me~~ (or proved to me on the basis of satisfactory evidence) to be the person~~(s)~~ whose name~~(s)~~ is/~~are~~ subscribed to the within instrument and acknowledged to me that he/~~she/they~~ executed the same in his/~~her/their~~ authorized capacity~~(ies)~~, and that by his/~~her/their~~ signature~~(s)~~ on the instrument the person~~(s)~~, or the entity upon behalf of which the person(s) acted, executed the instrument.

WITNESS my hand and official seal.

Signature [signature]

USHA K. POTTER
Comm. #1122070
NOTARY PUBLIC CALIFORNIA
ALAMEDA COUNTY
Comm Exp Jan 15 2001

**************************************************





00E1906"E9559E0

Date of Execution of Declaration for Patent Application: 5-22-00

(2) ______________________
(Inventor's Signature)

State of California )
)
County of Alameda )

On 05/22/00, before me, Usha K. Potter,
(*name and title of officer*)

personally appeared William A. Clark, ~~personally known to me~~ (or proved to me on the basis of satisfactory evidence) to be the person~~(s)~~ whose name~~(s)~~ is/~~are~~ subscribed to the within instrument and acknowledged to me that he/~~she~~/~~they~~ executed the same in his/~~her~~/~~their~~ authorized capacity~~(ies)~~, and that by his/~~her~~/~~their~~ signature~~(s)~~ on the instrument the person~~(s)~~, or the entity upon behalf of which the person~~(s)~~ acted, executed the instrument.

WITNESS my hand and official seal.

USHA K. POTTER
Comm. #1122070
NOTARY PUBLIC CALIFORNIA
ALAMEDA COUNTY
Comm Exp Jan. 15 2001

Signature ______________________

**************************************************************

Date of Execution of Declaration for Patent Application: 5/22/00

(3) ______________________
(Inventor's Signature)

State of California )
)
County of Alameda )

On 05/22/00, before me, Usha K. Potter,
(*name and title of officer*)

personally appeared Thor N. Juneau, ~~personally known to me~~ (or proved to me on the basis of satisfactory evidence) to be the person(s) whose name~~(s)~~ is/~~are~~ subscribed to the within instrument and acknowledged to me that he/~~she~~/~~they~~ executed the same in his/~~her~~/~~their~~ authorized capacity~~(ies)~~, and that by his/~~her~~/~~their~~ signature~~(s)~~ on the instrument the person~~(s)~~, or the entity upon behalf of which the person~~(s)~~ acted, executed the instrument.

WITNESS my hand and official seal.

USHA K. POTTER
Comm. #1122070
NOTARY PUBLIC CALIFORNIA
ALAMEDA COUNTY
Comm Exp. Jan. 15. 2001

Signature ______________________

**************************************************************



09593659 .061300

Date of Execution of Declaration for Patent Application: 5/22/00

(4) Allen W. Roessig
(Inventor's Signature)

State of California )
)
County of Alameda. )

On 05/22/00 before me, Usha K. Potter,
(*name and title of officer*)

personally appeared Allen W. Roessig, ~~personally known to me~~ (or proved to me on the basis of satisfactory evidence) to be the person~~(s)~~ whose name~~(s)~~ is/~~are~~ subscribed to the within instrument and acknowledged to me that he/~~she~~/~~they~~ executed the same in his/~~her~~/~~their~~ authorized capacity~~(ies)~~, and that by his/~~her~~/~~their~~ signature~~(s)~~ on the instrument the person~~(s)~~, or the entity upon behalf of which the person~~(s)~~ acted, executed the instrument.

WITNESS my hand and official seal.

Signature

USHA K. POTTER
Comm. #1122070
NOTARY PUBLIC CALIFORNIA
ALAMEDA COUNTY
Comm Exp. Jan. 15, 2001

*******************************************************************

09535930 . 061300